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The organic carbon isotopic and paleontological record across the Triassic–Jurassic boundary at the candidate GSSP section at Ferguson Hill, Muller Canyon, Nevada, USA

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Abstract

We present new litho-, bio-, and chemostratigraphic data from the Triassic–Jurassic (T–J) boundary section at Ferguson Hill (Muller Canyon), Nevada, USA. This section is a candidate for the base of the Hettangian Stage and thus the T–J boundary. Our measurements yield a 19 m thickness for the Muller Canyon Member of the Gabbs Formation. We recognize the Triassic–Jurassic boundary using the first appearance of *Agerchlamys*, and place it 9.6 m above the boundary between the Muller Canyon Member and the subjacent Mount Hyatt Member, with the first occurrence of the ammonite *Psiloceras tilmanni* occurring 0.9 m above this. Our organic carbon isotope record from this section shows two excursions toward lighter values, one at the T–J boundary, and the second in the lower parts of the Jurassic Sunrise Formation. These results are significantly different from a prior report on light stable isotopes from this section.

Keywords: Triassic; Jurassic; Carbon isotopes; Mass extinction

1. Introduction

Of the three major mass extinctions of the past 250 Ma – the Permian–Triassic; Triassic–Jurassic (T–J); and Cretaceous–Paleogene events – the Triassic–Jurassic mass extinction remains the least well-understood in terms of duration, extent, and cause (Hallam and Wignall, 1997). This lack of understanding is in no little part due to the paucity of well preserved boundary beds of this age, and there is still no accepted GSSP for the Triassic–Jurassic boundary. Another factor hampering progress has been (until recently) a lack of reliable information about the pattern of carbon-isotope changes across the T–J boundary. Since the analysis of carbon isotopes has emerged as a major tool in understanding the rapidity, magnitude, and in some cases, cause of mass extinctions, this absence has been notable. It was not

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until a few years ago that apparently reliable analyses of organic and inorganic carbon from densely sampled, stratigraphically complete sections began to appear (Pálfy et al., 2001; Ward et al., 2001; Hesselbo et al., 2002; Ward et al., 2004). From these it has become apparent that there is a recognizable and distinctive pattern of two negative isotope excursions in the stratigraphic vicinity of the Triassic–Jurassic boundary interval.

To further this work, in April 2003 we sampled a continuous section of 40 m which included the T–J boundary for carbon isotope analysis at the classic Ferguson Hill, Muller Canyon section in the House Range of Nevada (GPS 30,29,184 N; 118,05,030 W; see Hallam and Wignall, 2000, for further information about the locality), a site that has been proposed as a GSSP candidate for the base of the Hettangian stage and thus the Triassic–Jurassic boundary. We returned a second time in April of 2005. At the time of our initial sampling, we were unaware of any other efforts underway to define a carbon isotope stratigraphy from this section. However, before we had completed our isotopic analyses, a paper on the organic carbon isotopic record from a composite section with a total thickness of 25 m (the lower 5 m from Reno Draw, the upper 20 m from Ferguson Hill at Muller Canyon) appeared (Guex et al., 2003a,); later papers (Guex et al., 2003b, 2004) further described and discussed results from this original study. In these papers it was reported that the observed pattern of carbon isotopes extending from late Rhaetian through early Hettangian strata at Muller Canyon was typical of the Triassic–Jurassic interval previously reported from British Columbia and Europe. Because we had sampled from a single as opposed to composite section (the Ferguson Hill locality) with a total sampled thickness of 40 m, including samples in older rocks than those examined by Guex et al., we finished processing our samples, and we report on them here.

Our results are composed of three different suites of data. Firstly, we provide new detail on the lithology from this section; secondly, we present a record of organic carbon isotopes from a measured section of latest Rhaetian and earliest Hettangian age, with the lower 15 m previously un-sampled. Thirdly, we present new palaeontological data based on new macrofossil discoveries that we made during our two visits to this site. As we will show below, in addition to presenting these new data, our stratigraphic and carbon isotope measurements show significant differences to prior results. These differences bear on the timing and intercontinental correlation of the Triassic–Jurassic mass extinction.

2. Material and methods

The study location is shown in Fig. 1. The deeply weathered Muller Canyon member (Fig. 2) was trenched to a depth of ~ 1.5 m to get fresh material from a measured section beginning 15 m below the top of the Mt. Hyatt Member (Fig. 3) of the Gabbs Formation, and extending

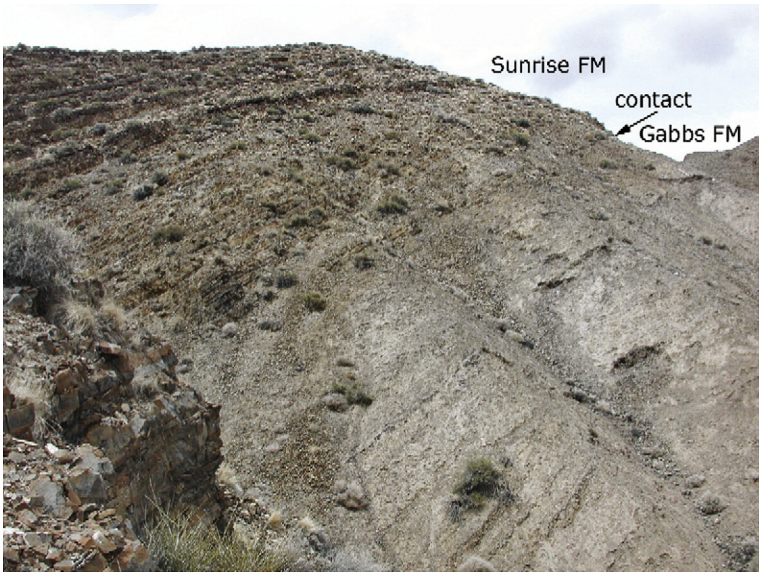

Fig. 1. View of Muller Canyon region showing the Muller Canyon Member of the Gabbs Formation (below) and Sunrise Formation (above). Black line marks contact between the units. The samples used in this study came from the small gully running nearly perpendicular to bedding from the lower right corner of the photograph. The Mount Hyatt Member of the Gabbs Formation is not visible in this photo, but is just beneath the lower right corner.

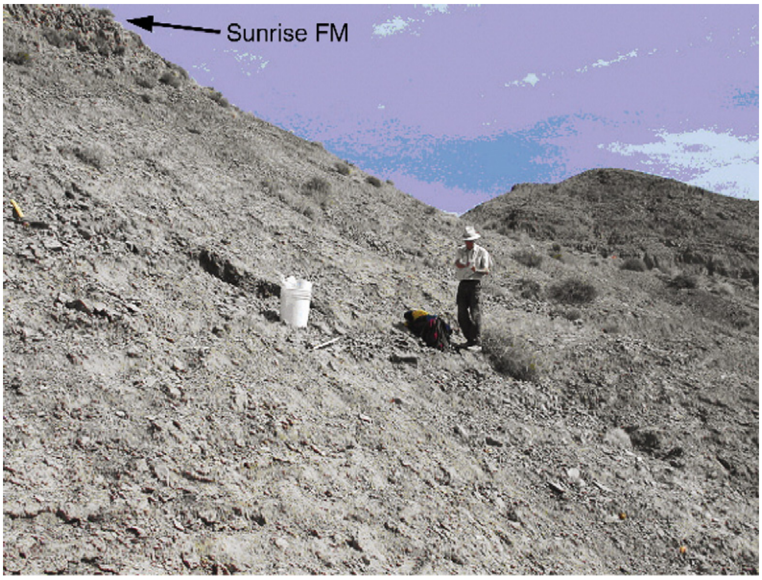

Fig. 2. Close up Muller Canyon Member lithology. The Triassic–Jurassic boundary is located at about the level of the white bucket. The base of the overlying Sunrise Formation is shown in the upper left corner of the figure.

through the Muller Canyon Member to a point 5 m up into the overlying Sunrise Formation (Fig. 1).

The stratigraphic section that we sampled was measured for its thickness in two ways. First, a tape was stretched across the outcrop perpendicular to bedding, and overall stratigraphic thickness corrected from dip measurements taken every 5 m. The section was then again measured with a Jacob staff with dip meter attached. Both methods resulted in repeatable and comparable measures of the individual members with variation of about 2 m per 100 m measured. Fossil collection was made from both surface discovery and quarrying at selected horizons.

The ratio of stable carbon isotopes ($^{13}C/^{12}C$) in sedimentary organic matter from rock samples was analyzed via elemental analyzer-continuous-flow isotope ratio

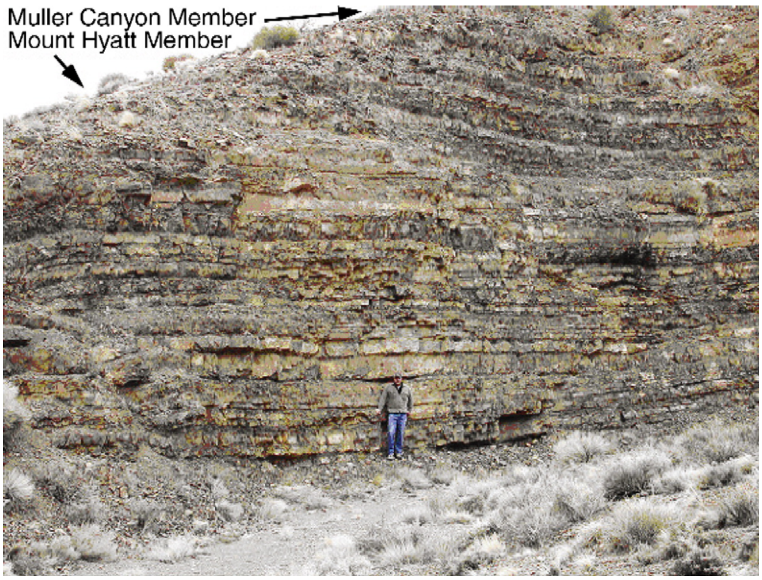

Fig. 3. Mount Hyatt Member (Rhaetian) in Muller Canyon area. The base of the overlying Muller Canyon Member is seen in the upper right side of the photograph. The lowest samples for isotope analysis in this study came from the base of this cliff.

mass spectrometry (EA-CFIRMS) at the Stable Isotope Research Facility (SIRF). SIRF is operated jointly by the Quaternary Research Center and the Astrobiology Program at the University of Washington.

Powdered samples were first acidified with an excess of 10% HCl and kept at 40° C for at least 12 h to remove inorganic carbonate material, especially recalcitrant mineral phases such as siderite ($FeCO_3$). Samples were then triple rinsed with ultrapure (>18 MÙ) deionized water and oven dried at 40 °C. Analyses were made with a Costech ECS 4010 Elemental Analyzer coupled to a ThermoFinnigan MAT253 mass spectrometer via a ThermoFinnigan CONFLO III gas interface. Isotope ratios are reported in standard delta (δ) notation relative to Vienna Pee Dee Beleminite (VPDB), where $\delta^{13}C = [[(^{13}C/^{12}C)\ \text{sample}/(^{13}C/^{12}C)\ \text{VPDB}] - 1] * 1000$. The standard deviation of sample replicates was 0.15‰ for $\delta^{13}C_{org}$ ($n=36$). Analytical precision based on routine analyses of internal laboratory reference materials was 0.15‰ for $\delta^{3}C_{org}$.

3. Results

3.1. Lithostratigraphy

The Muller Canyon exposure of the Triassic–Jurassic boundary interval is composed of the Mount Hyatt and Muller Canyon members of the Gabbs Formation and the Ferguson Hill Member of the overlying Sunrise Formation. This stratigraphy of Late Triassic and Early Jurassic strata in the Gabbs Valley Range was set on modern footing by Muller and Ferguson (1939), who established the formational terminology still in use today. Later work by Laws (1982) and Taylor et al. (1983) on the Gabbs Formation established a paleontological framework that placed the Triassic–Jurassic boundary within the Muller Canyon Member of the Gabbs Formation. Further collecting reported in Guex (1995), Hallam and Wignall (1999, 2000), and Guex et al. (2003a) increased the palaeontological data, but demonstrated that there was uncertainty about the placement of the T–J boundary, the thickness of the Muller Canyon Member, and the appropriate places in the section to formally define the contact of the Muller Canyon Member with its overlying and underlying stratigraphic units. All workers have used these member or formational transitions as reference marks for the base of their measured sections. Unfortunately, the two critical member transitions (Muller Canyon with the underlying Mount Hyatt and overlying Sunrise Formation) are both gradational in a facie comprising limestone and siltstone inter-beds, and this may explain some of the discrepancy in thickness of various units measured in the past.

The Mount Hyatt Member of the Gabbs Formation is characterized by carbonate beds and silty carbonate beds that are resistant to weathering. The overlying Muller Canyon Member is characterized by siltstone and calcareous siltstone that generally does not outcrop. The Ferguson Hill Member is marked by the reappearance of abundant carbonate beds. The contact between the Mount Hyatt and Muller Canyon members has an average dip of 35°, and the dip in the upper portion of the section shallows to an average of 26° (Figs. 1–3). Like other workers before us, we designate the contact between the underlying Mount Hyatt Member, and the superjacent Muller Canyon member as a tie point between the measured sections published by various authors. This placement does not need to be ambiguous, since there is a last distinct limestone typical of those lower in the Mount Hyatt overlain by a distinctive siltstone unit. This first metre of Muller Canyon Member strata is also recognizable because of its fossil content; it contains numerous belemnites, small nautiloids, and specimens of the ammonite *Choristoceras crickmayi*, among other Triassic ammonoids. We interpret this bed to represent a sea level high-stand. The bed is markedly more fossiliferous compared to overlying beds of the Muller Canyon Member and lithologically distinct from the limestone beds of the Mount Hyatt Member beneath, as well as the finer siltstone beds of the succeeding Muller Canyon Member. This unit, with the same fossil content and appearance, is also readily observable at Reno Draw (our observations made there in 2005). We designate the base of this bed as the “0” marker in our figures.

The succeeding beds of the Muller Canyon Member are composed of siltstone, calcareous siltstone, and, in its upper half, silty limestone, and they are medium to dark gray and brown in colour. The calcareous units are commonly sparry. Beds range from being fairly massive to flaggy, although the units are also highly fractured, making it difficult sometimes to recognize bedding. Gypsum commonly occurs as coatings within fractures and also forms more massive pockets in the rock. Beds in the upper part of the Muller Canyon Member are centimetre to metre in thickness, while decimetre to metre-thick beds dominate the lower portion of the member. Strata are commonly laminated, sometimes bioturbated (e.g. mm-scale burrows), and contain bivalves. The upper portion of the section, which begins at ~8.25 m, is dominated by thinner centimetre to decimetre-thick beds that are laminated at some levels. Thicker and more calcareous beds begin to appear above about 14 m in the section. The total thickness of the

Muller Canyon Member on our transect is just under 20 m. Our measurement thus differs from that of Taylor and Guex (2002) and Guex et al. (2003a,b, 2004), who found the Muller Canyon Member to be 15 m thick.

3.2. Biostratigraphy

Like all boundaries, the T–J boundary can be defined by a variety of paleontological markers. In fully marine sections the first occurrence of the ammonite *Psiloceras* is commonly used (Hallam and Wignall, 1997; Hallam, 2002), although bivalves and radiolarians are used as well. At Ferguson Hill, the type locality of both the Muller Canyon and Ferguson Hill members, as well as the location recommended for the global stratotype of the T–J boundary (and locality 7 of Guex, 1995), the biostratigraphy of the Late Triassic and Early Jurassic parts of the section has been repeatedly described (Guex, 1995; Hallam and Wignall, 2000; Taylor and Guex, 2002; Guex et al., 2004). Psiloceratid and other Hettangian ammonites are common in the lower Sunrise Formation at Muller Canyon, and have been found in limited numbers in the upper parts of the Muller Canyon Member. *Psiloceras tilmanni, P. spelae*, and *Juraphyllites*, taxa considered as diagnostic of the Jurassic, are figured as occurring at 8 m above the last undoubted Triassic species (*Choristoceras crickmayi* and *Arcestes gigantogeleatus*) in Guex et al. (2003a,b).

At the Ferguson Hill section, the lowest significant 'post-extinction' macrofossil that we recovered was the pectinacean bivalve *Agerchlamys boellingi* (data herein and Taylor and Guex, 2002; Guex et al., 2003a). As in other basal Triassic–Jurassic boundary intervals, bivalves are commonly the only macrofauna present in the "Pre-Planorbis" interval, below the lowest appearance of Jurassic psiloceratid and neophyllitid ammonoids. Similar patterns of lowest appearance of pectinacean bivalves, including species now deemed to belong to *Agerchlamys*, occur in the classic Triassic–Jurassic boundary sections at Kendlbachgraben and Tiefenbachgraben Austria (Golebiowski and Braunstein, 1988), the Grotta Arpaia section near Portovenere, Italy (Cartwright, 1995), Utacumba, Peru (Hillebrandt, 1994), and in several other North American localities (McRoberts, 2003). These low-diversity post-extinction Jurassic bivalve faunas are ecologically homogenous, comprising mostly pectinaceans (scallops) such as *Agerchlamys* and forms attributed to "*Chlamys textoria*", and likely employed generalist (r-selected) strategies. McRoberts (2003, 2004) termed this ubiquitous occurrence of pectinacean bivalves a "clam

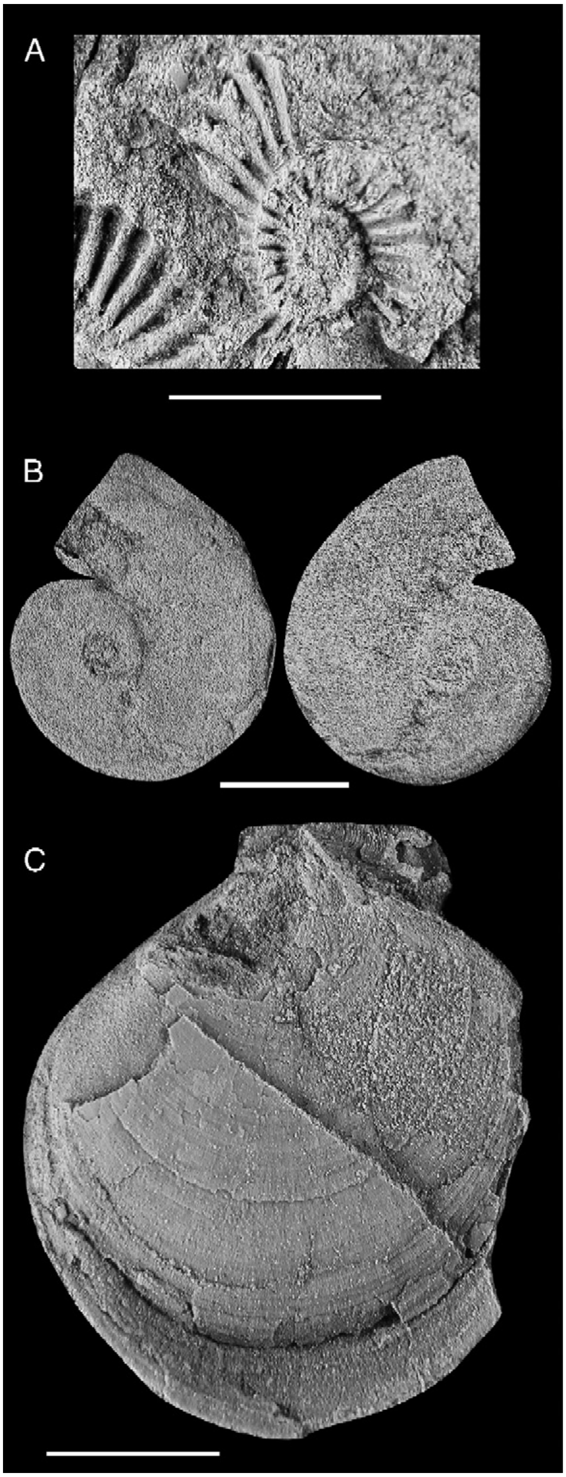

Fig. 4. Photographs of important index fossils and stratigraphic height of discovery above the Mount Hyatt–Muller Canyon boundary from Ferguson Hill, Nevada, USA. A. Possible *Choristoceras crickmayi*, 1 m; B. *Psiloceras sp.* 10.5 m; C. *Agerchlamys boellingi*, 9.6 m.

spike" and suggested that it may be the marine equivalent of the continental "fern spike" associated with both the end-Triassic (e.g., Olsen et al., 2002) and end-Cretaceous (e.g., Fleming and Nichols, 1990) events. We have recovered the lowest undoubted specimen *A. boellingi* (Fig. 4) at 9.6 m above the base of the Muller Canyon Formation.

3.3. Organic carbon isotope record

Samples were analyzed from 76 separate stratigraphic horizons from our 45 m thick measured section. All samples were analyzed multiple times, and those with heavier values were repeatedly treated with acid to ensure that spurious heavy values were not being obtained because of contamination by carbonate. The results of our organic carbon isotope investigation are shown in Fig. 5.

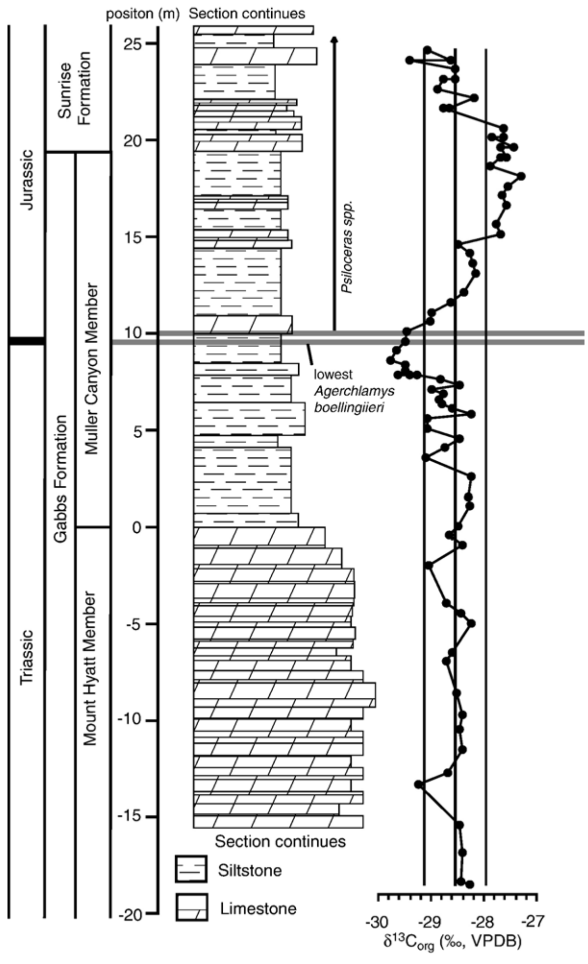

Fig. 5. Measured section at Ferguson Hill, Muller Canyon showing our litho-, bio-, and chemostratigraphic results. Width of lithological units relates to degree of induration as seen in field. Grey line marks base of Jurassic as picked by ammonites, whereas the first appearance of *A. boellingi* is favored here for the base of the Jurassic.

In the lower 26 m of the 45 m thick measured section (between positions−18.0 and 7.8 m, Fig. 5), $\delta^{13}C_{org}$ has a nearly constant value of −28.6‰ (VPDB), with a standard deviation of only 0.3‰ (n=34). There are three excursions in the $\delta^{13}C_{org}$ data moving upwards through the top 17 m of the section: between 7.8 m and 9.0 m, $\delta^{13}C_{org}$ drops steadily to −29.8‰ (VPDB), then increases steadily to−27.3‰ (VPDB) at 18.5 m, and finally drops to −29.1‰ at 25 m. Our isotopic results from within the Mt. Hyatt Member show no significant isotopic excursions.

While the shape of the isotope curve that we recovered resembles that of Guex et al. (2003a,b, 2004) the positions of the two negative excursions are at stratigraphically different levels. The two data sets also differ in average observed values. We discuss the ramifications of these findings in the next section.

4. Discussion

Any reference section must show as many attributes allowing correlation as possible. An ideal section would contain macrofossils (ammonites and other molluscs), microfossils (conodonts and radiolarians), as well as having bentonites, an unaltered carbon isotope signal, and an unaltered paleomagnetic signal. Finally, even having all of these attributes is useless if the section is inaccessible for geographic, altitudinal, or political reasons. While the Ferguson Hill section shows few conodonts or radiolarians, and there has been no report of dateable ashes or a successful attempt at magnetostratigraphy, the section does have an abundant macrofossil record, a chemostratigraphic record, and is readily accessible by car. Compared to other sections examined to date it must be considered a front-runner for the site of the Triassic–Jurassic GSSP, and for this reason ambiguities concerning its stratigraphy must be resolved.

The presence of two negative anomalies in organic carbon straddling the biostratigrapically defined Triassic–Jurassic boundary at the Ferguson Hill locality in Muller Canyon, obtained first by Guex et al. (2003a,b, 2004), as well as in our data reported here, demonstrates an increasingly familiar pattern previously observed from Kennecott Point, Canada (Ward et al., 2001; Ward et al., 2004), St Audrie's Bay, England (Hesselbo et al., 2002), and Csovár, Hungary (Pálfy et al., 2001). While this similarity may be simply coincidental, it is far more likely that the record from Muller Canyon represents another section in the growing number of Triassic–Jurassic boundary sections from which reliable carbon isotope records have been obtained. All four records appear to be complete across the Triassic–Jurassic boundary, have been studied biostratigraphically, and have a healthy isotope sample density: Csovár — 0.97 samples m^{-1}, Kennecott Point — 3.1 samples m^{-1} (across the 21 m boundary interval); St Audrie's Bay — 4.5 samples m^{-1}; Muller Canyon (this study) — 1.8 samples m^{-1}. Sampling density is particularly important to differentiate true excursions within the isotope record from sporadic single-point aberrations. These four T–J boundary records show two significant negative $\delta^{13}C_{org}$ excursions with similar magnitude and stratigraphic spacing at or near the Triassic–Jurassic boundary. The similarities in these records indicate that the $\delta^{13}C_{org}$ variations represent global-scale perturbations of the carbon cycle.

There are important discrepancies between our work and previous work in the Gabbs Range, in terms both of relative stratigraphic position of the two isotopic excursions, as well as in isotopic values for the same parts of the overall curve, especially in those samples from the Rhaetian and earliest Hettangian levels of the Muller Canyon Member.

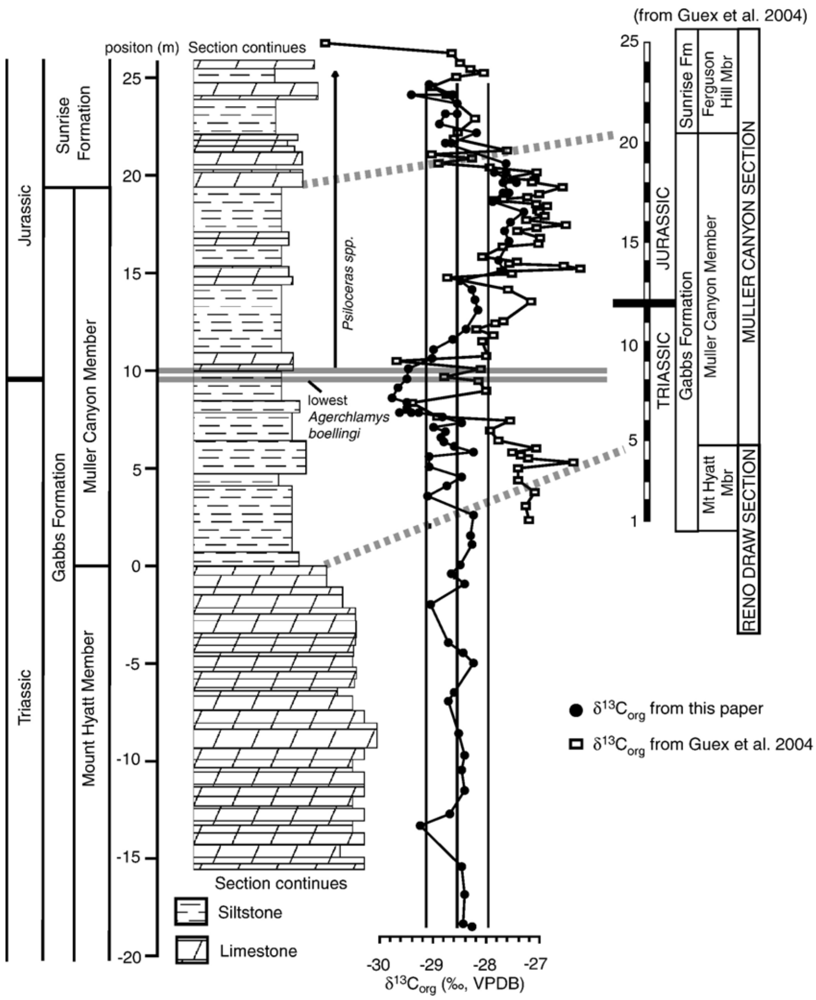

Fig. 6. The stratigraphic section and $\delta^{13}C_{org}$ data measured by Guex et al. (2004) overlain on the section and $\delta^{13}C_{org}$ from this paper. The two sections are aligned such that the structures of the $\delta^{13}C_{org}$ curves match. Note that all the $\delta^{13}C_{org}$ data presented in this paper were measured from samples collected from the same section (i.e. the Muller Canyon section), while the Guex et al. data are from two sections: Muller Canyon Member and Ferguson Hill Member samples were collected from the Muller Canyon section, and Mount Hyatt Member samples were collected from the Reno Draw section. The Reno Draw and Muller Canyon sections sit in structurally different blocks (Taylor et al., 1983). The differences in the two $\delta^{13}C_{org}$ curves may be a result of incomplete de-carbonation (and thus the presence of recalcitrant, isotopically heavy material such as siderite) on the part of Guex et al. Furthermore, Guex et al. (2004) appear to have missed the lowermost ~8 m of the Muller Canyon Member at the Muller Canyon section. These units are not strongly competent, and the boundaries between units are somewhat indistinct.

First, the excursions reported by each group are found at different stratigraphic levels relative to the T–J boundary. The Guex et al. (2004) results (Fig. 6, right) show the lower negative excursion to be entirely in the Triassic, terminating 4 m below the lowest specimen of *Psiloceras tilmanni*, which occurs at 8 m above the boundary of the Mount Hyatt and Muller Canyon Members (Guex et al., 2004, Fig. 2). Our results show that this negative excursion is initiated less than 2 m below the first appearance of *Agerchlamys* and that the first *Psiloceras* occurs just above the most negative carbon isotope values. The excursion's minimum thus effectively coincides with the T–J boundary at this site. Similarly, the upper excursion is at different levels in the two papers. In Guex et al. (2004), values begin to decline at about 12 m above their Mount Hyatt–Muller Canyon boundary, and remain light to the top of their section. Our upper negative excursion is higher in the section, initiating near the boundary between the Gabbs and Sunrise Formations, or at about 19 m. By moving the Guex et al curve up 8 m (which we have done in our Fig. 6) the two excursions essentially overlap. In summary, compared to our work, the isotopic pattern shown in Guex et al. (2003a,b, 2004) appears to be displaced downward.

Secondly, in general our carbon isotope values are lighter, especially in the lower parts of the sampled sections. In processing our samples we found that significant amounts of siderite as well as calcium carbonate were present in the samples. We found it necessary to heat samples during de-carbonation in order to achieve a more complete reaction, and it is not clear whether Guex et al. followed an equivalent procedure. Incomplete removal of carbonate minerals from samples before organic carbon isotope analyses will cause spurious, heavy values, and this might be the case for Guex et al. samples from below the Sunrise Formation.

Also troubling is the difference in measured thickness of the Muller Canyon Member between sections published by Taylor and Guex, 2002, and Guex et al. (2003a, b, 2004) (approximately 15 m total thickness) compared to measurements of the same stratigraphy by Hallam and Wignall (1999, 2000), and in this paper (both finding about 19 m). This may be due either to different definitions of the lower and upper boundaries of the Muller Canyon Member, or erroneous measurement of the strata. Our group meticulously re-measured the Muller Canyon Member during a return trip in 2005 and again found the member to be 19.3 m thick, as reported here. Whatever the reason, the isotopic curve shown in the three Guex et al. papers differs from ours. If this section is to be accepted as a GSSP, these differences must be reconciled.

Acknowledgements

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